Universal MIMO-OFDM SDR for Mobile Autonomous Networks (OPTIONS)

FINAL REPORT

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1. Introduction

This report presents Pulsar's (Pulsar was recently incorporated as Silvus Communication Systems, Inc.) progress on NAVY SBIR topic number: N04-109, TITLE: Universal MIMO-OFDM SDR for Mobile Autonomous Networks as part of the Phase 1 options granted on January 15th, 2005. It will present the findings of our phase-1 options work and will provide a summary of tasks as part of a potential Phase 2 grant.

In November 2004, as part of the Phase 1 final report, Pulsar reported the main accomplishments of the phase 1 effort as follows:

- Robust and highly agile software defined radio architecture has been identified along with a candidate set of algorithms that will enable end to end MIMO communications. These algorithms have gone through testing and verification.
- A complete end to end simulation has been created that implements all transmitter and receive algorithms in sample accurate simulation environment, and the resulting system performance has been simulated in characteristic environments. The results are quite positive and provide insight into the capability of both MIMO and the proposed architecture.
- Limited field trials using a non real time testbed have been carried out. In these trials, the simulation code was used to generate packets which were then transmitted in real time over the air. The receiver captured the transmissions and passed the received samples to the PC for processing. Over the air data rates of 160 Mbps were observed in typical indoor environments, with a small 1 mW TX power. Both indoor and outdoor stationary trials were carried out.

This effort was extended in the Phase 1 option to move towards a real-time implementation of the MIMO-OFDM SDR. As part of the Phase 1 option a detailed architectural level design and analysis of the system was conducted to evaluate the computational complexity and identify the required hardware platform for the system. The main topics addressed under the Phase 1 option are:

1) **A detailed component level design of the RF transeivers.**
2) **Detailed calculations on the GOPS (Giga Operations Per Second) required for MIMO demodulation.**
3) **Overhead optimization experiments resulting in a packet structure with minimal training and piloting overhead.**

Tasks 1 and 2 were detailed in the interim report. Task 3 is being presented in this report. For the sake of completeness task 1 and 2 are repeated in this final report.

2. RF Transceiver Design

The radio for the MIMO-OFDM SDR was designed to operate in 2 different bands, the 5 GHz and the 2.4 GHz bands. A DDFS [1][2] allows the center frequency (carrier frequency) to be chosen over a wide range of frequencies; 195 MHz band at 5 GHz and 80 MHz band at 2.4 GHz. The overall frequency plan of the system is shown in Figure 1. The input to the RF frontend of the transmitter is a 25 MHz IF signal.

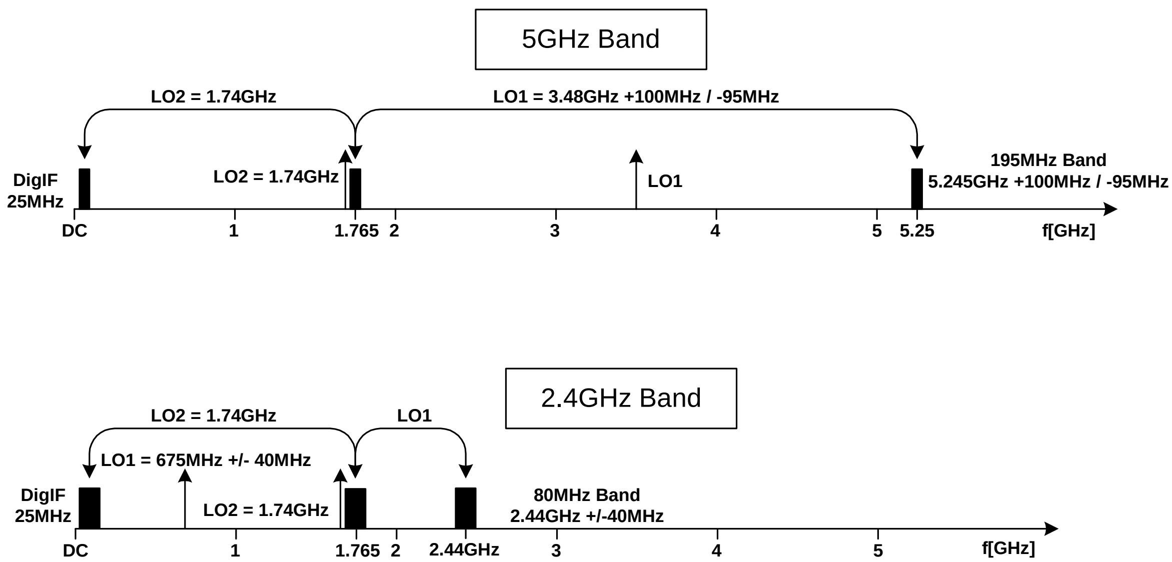
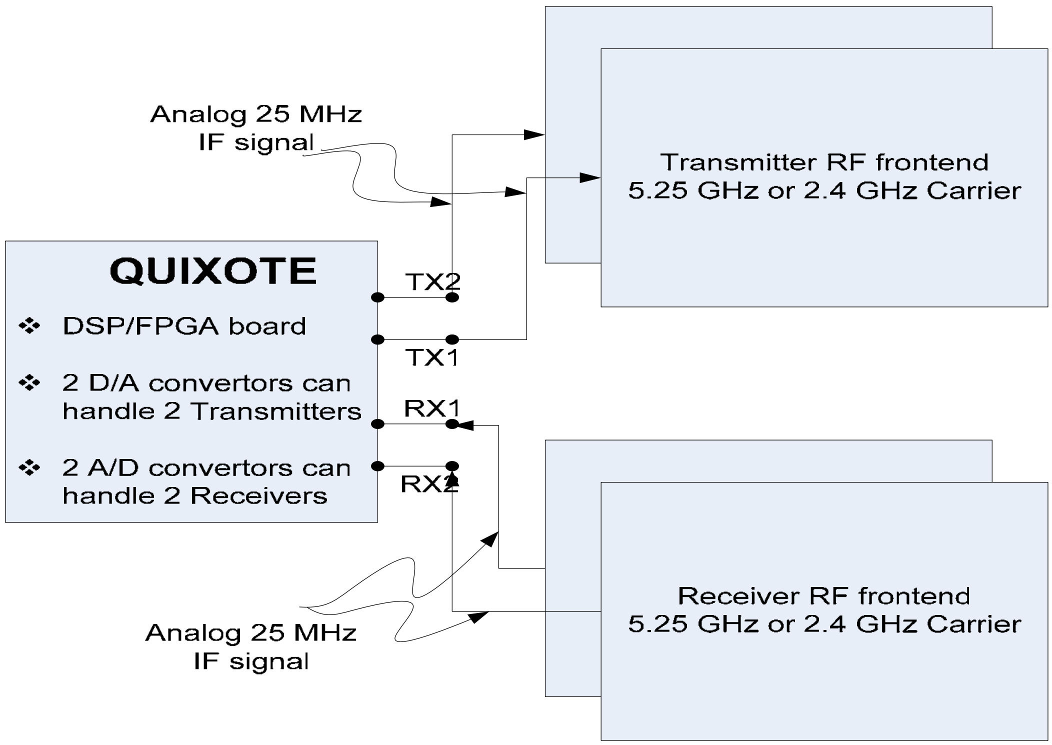


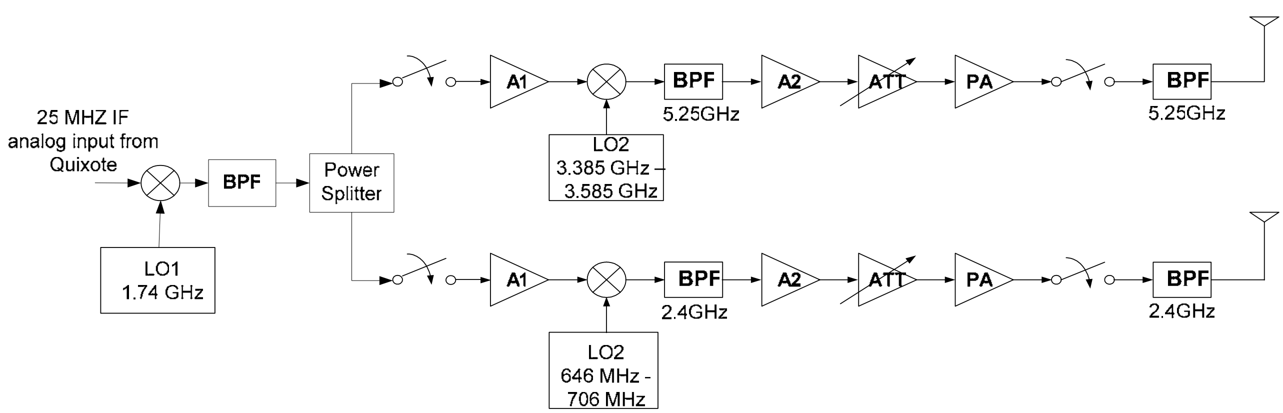
Figure 1 Frequency plan of the MIMO-OFDM SDR

A detailed block diagram of the radio is given in Figure 2. Figure 2(a) shows the block diagram of the baseband system. The transmitter RF frontend is shown in Figure 2(b). The system is based on a digital IF architecture. The data is modulated on the Quixote board which has a TI 6416 fixed point DSP and a Xilinx Virtex II-6000 FPGA. The baseband in-phase and quadrature samples are digitally upconverted to an IF of 25 MHz, summed and passed through the Digital to Analog (D/A) convertors on the Quixote board. The Quixote board has 2 D/A and 2 A/D convertors and can drive 2 RF transmitter frontends. Multiple such systems can be cascaded for larger MIMO configurations. The transmitter RF frontend is a two step up-conversion implementation with an Intermediate Frequency (IF) at 1.74 GHz [3]. In a two step up-conversion transmitter, the signals are first up-converted to the IF, then with a second mixer to the carrier frequency. This segmentation of the up-conversion process relaxes the specification on the mixer. The two transmitters on one RF board run on a common time-base given by a Temperature Compensated Crystal Oscillator (TXCO). The LO signals feeding the mixer are generated on each of the boards. The input is first mixed with a 1.74 GHz signal to move it to 1.765 GHz. A power splitter divides the RF chain into a 5 GHz chain and a 2.4 GHz chain. A switch (controllable from software) is used to choose the operating band. The 1.765 GHz IF signal is mixed with the 3.48 GHz LO signal to move it to 5.25 GHz and is mixed with 646 MHz LO signal to move it to 2.4 GHz carrier frequency. The combination of a variable attenuator (ATT), Power Amplifier (PA) and switch are used to control the transmit power. The

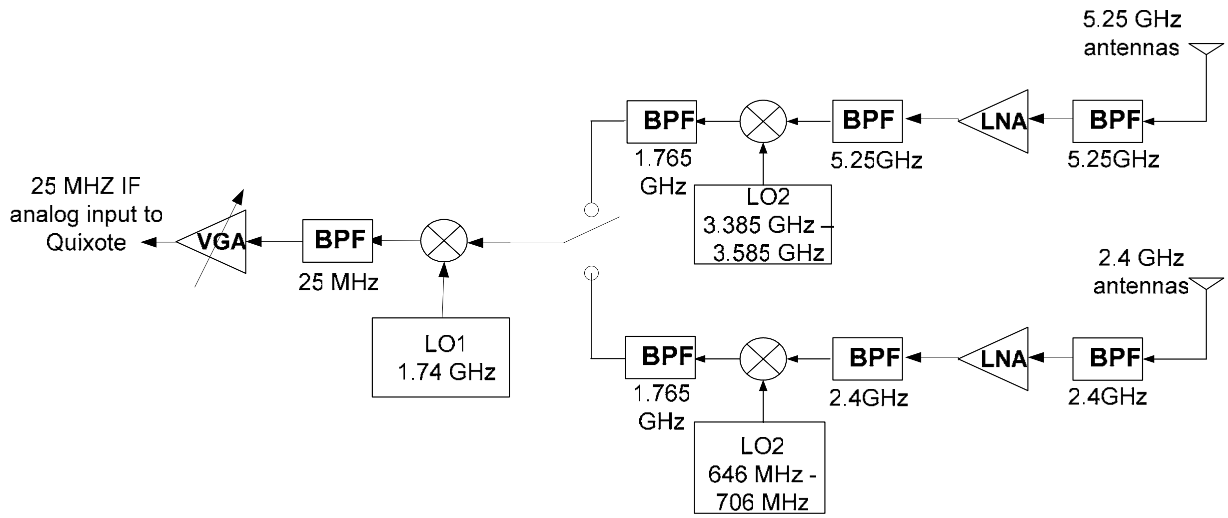
antenna is a 5.25GHz or 2.4 GHz WLAN monopole antenna with linear polarization and an omni-directional azimuth pattern.



(a)



(b)



(c)

Figure 2 The MIMO-OFDM SDR architecture. (a) The overall block diagram (b) The transmitter RF frontend (c) The receiver RF frontend

The detailed block diagram of the RF to low IF down-conversion chain of the receiver is shown in Figure 2(c). It is a heterodyne receiver [3] with an Intermediate Frequency at 1.765 GHz. The receiver is also capable of operating in 2 bands. A switch (controllable from software) allows the choice of the operating band. The receiver RF boards can handle 2 RF streams. Multiple boards can be cascaded to build larger MIMO configurations. Optionally, the receiver can be run on the same time-base as the transmitter to help evaluate algorithms without the overhead of synchronization. VGAs are used to control the received power with the help of an Automatic Gain Control (AGC) loop. The 25 MHz IF signal is input to the Quixote board which has 2 A/D converters sampling at a rate of 100 MSPS. The I/Q demodulation and downconversion to baseband and demodulation happens on the Quixote board. The demodulated data is transferred to the host PC via the PCI bus.

Similar to the architecture of the communication system, detailed in the Phase 1 final report, the architecture of the transceiver is extremely flexible and all the parameters can be controlled from a graphical user interface. The USB connection is used to download the parameters from the host PC to the transceiver boards.

As part of the Phase 1 options, we have completed a detailed specification of the architecture and selection of components for the transmitter and receiver boards.

3. Computational Complexity of MIMO Demodulation

Although MIMO systems promise significantly improved spectral efficiency and throughput gains they are also computationally very complex. A detailed analysis of the computational complexity of the

modem was performed to evaluate the appropriate architecture for implementation on the DSP and on the FPGA. Based on this analysis the various MIMO-OFDM demodulation algorithms will be partitioned between the DSP and the FPGA. The partitioning will be determined by the system bandwidth and throughput requirements of the communication system.

Various MIMO decoding architectures such as MMSE, QR-MMSE, LMS, RLS [4], QR-RLS, Inverse QR-RLS and VBLAST [6] were evaluated for computational complexity. The GOPS (Giga Operations Per Second) computation calculates the total number of real multiplications per second. This is shown graphically in Figure 3. A SISO-OFDM system (1x1) requires about 0.3 GOPS for all the algorithms. But as the MIMO configuration increases the various algorithms show significantly different and increased computational requirements. Consider the case of the RLS algorithm. In a system with a signal bandwidth of 25 MHz, a 2x2 RLS system requires 2.5 GOPS but a 4x4 RLS system requires 19.5 GOPS. The LMS algorithm in contrast requires only about 3 GOPS and is the least complex in terms of computation. But LMS has a very high training overhead. In a packet mode wireless communication system such a high training overhead is prohibitive. On the other hand RLS has higher complexity compared to LMS but requires significantly (an order of magnitude) less number of training blocks. The other solutions such as MMSE require far fewer training blocks but have significantly higher computational complexity.

Based on the above analysis two architectures (the Inverse QR-RLS and the MMSE solution) were short listed for further detailed architecture evaluation. Both of these algorithms were mapped to systolic array architectures (as part of the Phase 1 option) in an effort to compute the FPGA utilization and map them to the fewest number of FPGAs.

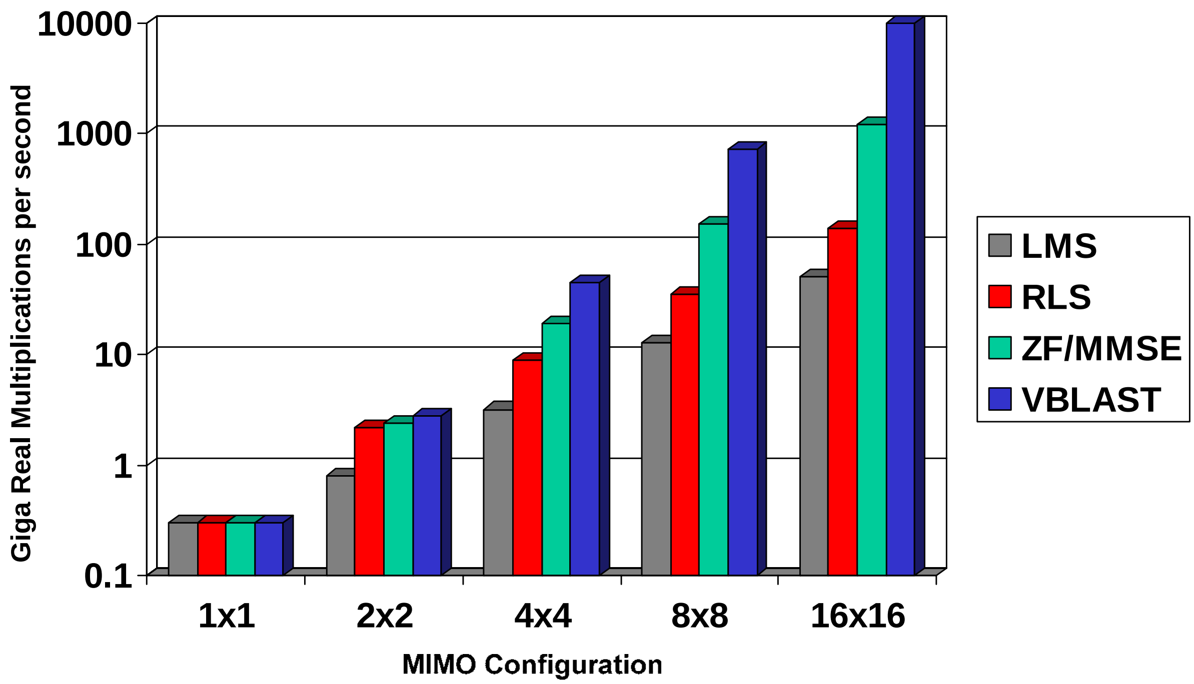


Figure 3 Complexity of MIMO decoding algorithms

Table 1, FPGA and DSP Requirements

Operation	Xilinx 10 MBaud		TI DSP Requirements	
	Slices	Memory	MIPS @ 10 MBaud	MIPS @ 25 MBaud
Variable Rate Filtering	159/ant	0	0.5 GOPS/ant	1.4 GOPS
Low Pass Filter	1368/ant	0		
DDFS	52/ant	1 Kb	30 MOPS/ant	75 MOPS/ant
FFT (1024)	884/ant	54Kb/ant	60 MOPS/ant	150 MOPS/ant
2x2 RLS MIMO decoding	5904	96 Kb	1 GOPS	2.5 GOPS
4x4 RLS MMO decoding	11146	320 Kb	7.68 GOPS	19.2 GOPS
Viterbi Decoder	11284	576 Kb	1.4 GOPS	3.5 GOPS
Turbo Decoder	140100	14400 Kb		
2x2 VBLAST MMSE			1.2 GOPS	3 GOPS
4x4 VBLAST MMSE			30.7 GOPS	76.8 GOPS

Table 1 summarizes the computational complexity of each of the schemes along with other components of the receiver, such as the Turbo Decoder, Viterbi Decoder, DDFS, etc. Both the complexity of FPGA implementation and DSP implementation are listed in the table. A 2x2 RLS MIMO decoding algorithm requires 5904 slices of a Virtex II FPGA whereas a 4x4 system requires 11146 slices. In a MIMO-OFDM system each subcarrier needs to be MIMO decoded. Therefore multiple such processing units are required. However, depending on the bandwidth multiple subcarriers can be time multiplexed onto the same MIMO decoder module. A Xilinx Virtex II 6000 FPGA has approx 30000 slices. Based on this analysis we believe a 2x2 MIMO-OFDM system can be implemented on 2 Xilinx Virtex II 6000 FPGAs and 3 to 4 FPGAs are required for a 4x4 MIMO-OFDM communication system.

4. Overhead in a MIMO-OFDM System

Overhead in a packet (burst) mode communication system must be carefully analyzed, and optimized. In general overhead at the physical layer relates to the additional signaling necessary to detect, acquire, and track variations in the channel as well as the drifts in the state of the transmitter or receiver. In the packet structure that we developed for the SDR, Figure 4 below, the overhead consists of the AGC and block boundary detection headers, the specialized OFDM symbols for course frequency and timing synchronization, the fine synch and the channel estimation header, and finally the pilot channels used for carrier tracking (shown as vertical black lines in the figure). These are rather generic blocks that appear in almost all communication systems. In wireline communications, such as voiceband modems, or DSL systems, the amount of time spent on initial link establishment could be rather long, and could be measured in tens of seconds. This is because the channel itself is very slowly varying. Its rate of change can be measured in hours, and is due to changes in the temperature or humidity of the environment. In wireless burst communications however, the rate of change of the channel could be as high as 500 Hz (for example when communicating with a low altitude UAV at high carrier frequencies). A 500 Hz rate of change implies that the channel is entirely different after a mere 20 milliseconds. This implies that packet

detection, acquisition and tracking needs to be carried out at pretty much the beginning of every transmission. If the payload is short, such as in cases when a mere key stroke needs to be communicated to the source, then the overhead associated with the transmission of each packet must be minimized.

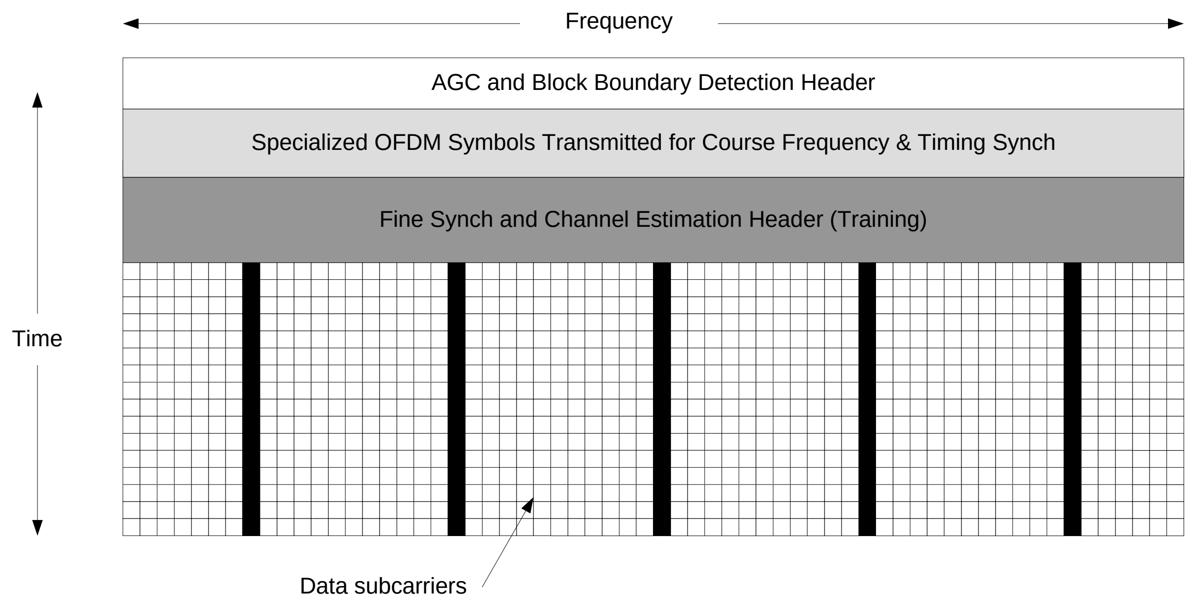


Figure 4. A time-frequency plot of the packet structure

In the work to date we had used a recursive least squares (RLS) approximation to the MMSE (minimum mean squared error) solution for channel estimation and tracking. RLS algorithms [4] are well known for their fast convergence properties relative to their LMS (least mean square) counterparts. They also help reduce the peak computational requirement by spreading the computations across multiple samples. Our investigation supported results obtained in [5] in terms of the convergence time of the RLS algorithm in a MIMO environment. Figure 5 shows the convergence of the RLS algorithm for a 2x2 MIMO system, and indicates that 15 OFDM blocks are sufficient to achieve full convergence of the algorithm. Our investigations for larger MIMO configurations showed that for a 4x4 system a minimum of 20 OFDM blocks are needed and in certain cases as many as 25. Although such numbers seem reasonable at first glance, we must note that when operating in a 20 MHz bandwidth and using a moderate 256 point FFT for OFDM modulation, each OFDM block will be 12.8 micro seconds, which translates into 256 micro seconds just for the transmission of the channel training overhead. To this we need to add another 50 microseconds for the AGC, block boundary detection, and the course acquisition loops, bringing the overall total to 306 micro-seconds. Given the power of MIMO based systems to achieve exceptional spectral efficiencies. A 20 MHz, 4x4 MIMO system could easily achieve 320 Mbps of peak over the air data rate (assuming 16-QAM constellations on each subcarrier). Even if a rate ½ convolutional code is used, the user data rate is still on the order of 100's of Mbps. Which means that short message on the order of, say 100 bytes, will be transmitted in approximately 5 micro-seconds.

Comparing the 306 micro-seconds of overhead to the 5 micro-second message duration, it is clear that the overhead for RLS based channel estimation is excessive.

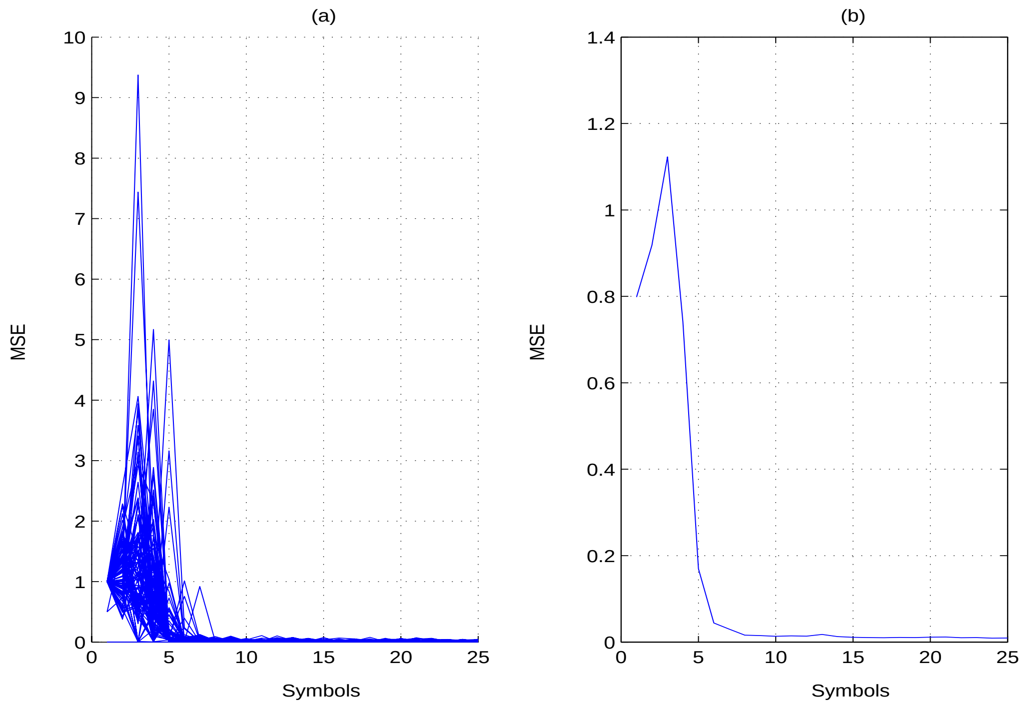


Figure 5 (a) Learning curves of individual subcarriers in a 2x2 MIMO system (b) Average learning curve of all subcarriers

In [5] the authors also investigated the overhead associated with carrier frequency tracking in a typical MIMO system as well. The results are summarized in Figure 6. The reason for the higher throughput of the MIMO configurations relative to the SISO configuration has to do with the MIMO gain, and the 2x improvement in spectral efficiency offered by a 2x2 MIMO system. As can be seen from the plot, the penalty for increasing the number of pilot subcarriers beyond the optimum is not as sever as that of the header. Consequently we will continue with the previous approach of devoting 5% to 10% of the overall subcarriers to act as continuous pilot subcarriers.

OFDM systems, and in particular in MIMO OFDM systems are extremely sensitive to carrier frequency offsets and phase noise in the carrier frequency. Carrier frequency offset and phase noise break the orthogonality of the OFDM subcarriers and cause inter-carrier interference from not just the neighboring subcarriers, but rather from all subcarriers. In a MIMO system this problem is exacerbated since all subcarriers from all transmit antennas will interfere with one another. However, with a good coarse carrier recovery scheme and a tight feedback loop, these problems are mitigated.

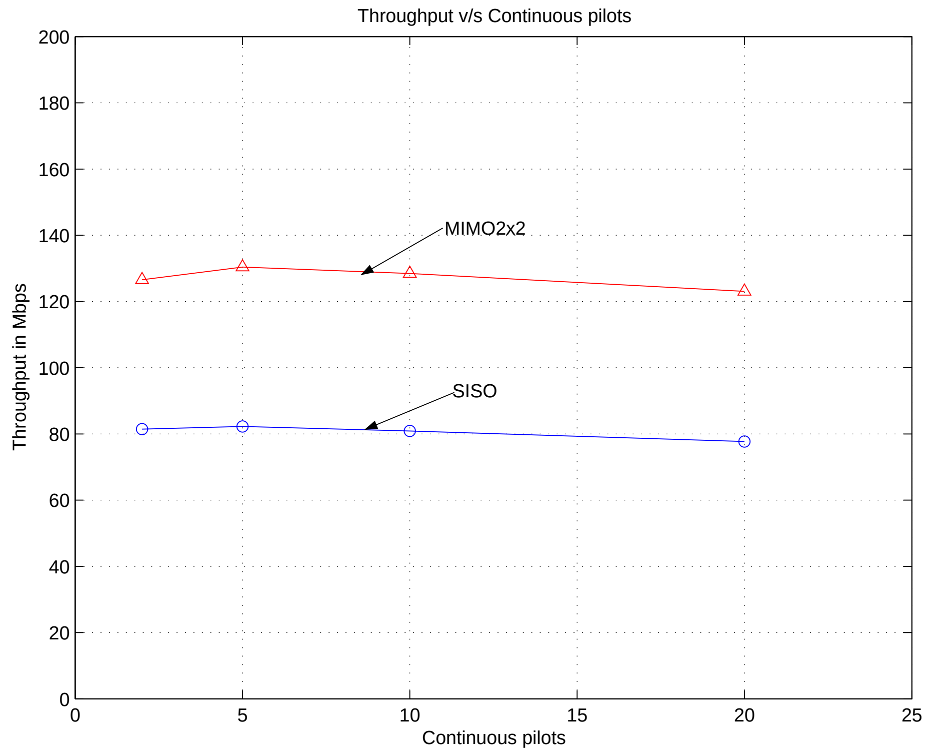


Figure 6 Throughput v/s continuous pilots with 25 training symbols

In the Silvus SDR, the user has full control over the number and configuration of the antennas to be used, the number of subcarriers, the constellation size, the amount of cyclic prefix, the number of pilots and the training overhead. The training symbols and the pilots constitute overhead and to maximize the user data rate these need to be minimized.

Alternative approach to MIMO decoding

In an attempt to minimize the channel estimation overhead, we considered a change in both the packet structure and the algorithms used for channel estimation and inversion. As shown in Figure 3 the complexity of MIMO decoding algorithms is a very important criterion in designing the overall MIMO-OFDM communication system. For packet mode communications there is another criterion; the training overhead. A tradeoff between the complexity of MIMO decoding and the excessive training overhead that the adaptive algorithms require is essential. To evaluate this tradeoff, the packet structure required for an MMSE based MIMO decoder was studied. The MMSE solution requires the channel to be estimated. This channel estimate is then used to compute the weight matrix (also referred to as the channel inverse since it is used to cancel the effects of the channel) which is used to cancel the effects of the MIMO channel. The amount of training required depends on the channel estimation algorithm used. In general the amount of training required to estimate the channel scales linearly with the number of transmit antennas. Depending

on the robustness of the channel estimation algorithm the number of training blocks required may be smaller.

The next generation wireless LAN standard, called 802.11n is also based on MIMO-OFDM with up to 4 transmit antennas. This standard is currently undergoing standardization and has 2 competing proposals with different preamble structures; The Tgn-Sync proposal and the WWise proposal. Both of these were studied as part of the overhead analysis study. In both the proposals the number of training symbols scale linearly with the number of transmit antennas. In the Tgn-Sync proposal there are 2 training symbols when there is 1 transmit antenna. With 2 transmit antennas this grows to 4 training symbols. The maximum number of transmit antennas is 4 in which case the number of training symbols is 8. In contrast, the WWise preamble uses just 1 training symbol for the 1 transmit antenna case. This scales linearly with the number of transmit antennas. For the 4x4 case, the total number of training symbols is 4. Although the number of training symbols is much more optimal in the case of WWise, the complexity of channel estimation algorithm is much higher and the quality of channel estimates in the presence of analog impairments is also worse compared to the Tgn-Sync case. Based on this analysis we decided to use the packet structure similar to the Tgn-Sync system for the Silvus SDR. Table 1 summarizes the results of the overhead analysis study and the results of the complexity analysis.

Table 1 Comparison of training overhead and MIMO decoding complexity for various 4x4 MIMO-OFDM systems

	RLS	MMSE/Tgn-Sync	VBLAST/Tgn-Sync	MMSE/WWise	VBLAST/WWise
MIMO decoder complexity	9 GOPS	12 GOPS	18 GOPS	12 GOPS	18 GOPS
Training symbols for channel estimation	25 OFDM symbols	8 OFDM symbols	8 OFDM symbols	4 OFDM symbols	4 OFDM symbols
Percentage overhead for a packet of 75 symbols	33.33%	10.6%	10.6%	5.3%	5.3%
Channel estimation complexity	LOW	LOW	LOW	HIGH	HIGH
Channel estimate quality	GOOD	GOOD	GOOD	POOR	POOR

Based on this analysis, we decided to employ an MMSE MIMO decoder and a preamble/packet structure that uses 2 OFDM symbols per transmit antenna, for the Silvus SDR. This system minimizes the training and piloting overhead for a moderate increase in MIMO decoder complexity. A systolic array architecture has also been worked out for FPGA implementation for the MMSE MIMO decoder.

5. CONCLUSIONS

This report presents the work accomplished by Silvus Communication Systems under the phase 1 option. Building further on the MIMO-OFDM SDR effort in Phase 1, the option extends this by evaluating the complexity of various algorithms for real-time implementation on the DSP as well as the FPGA. Detailed component level architecture specification of the transceiver was also completed.

This effort will be further extended in a possible Phase 2 grant to complete the implementation of a very flexible multi-band, multi-antenna SDR.

6. Summary & Future Work

The following is a list of achievements during the phase one effort:

- Identified a highly flexible SDR hardware architecture with the following features
    - Dual band TDD transmission
    - Variable bandwidth (bandwidth agility)
    - Variable center frequency (frequency agility) within the prescribed bands
    - Parameterizable OFDM modulation
    - Programmable NxM MIMO configuration.
- Identified all receiver algorithms for a MIMO OFDM system and included them in a complete end to end sample accurate simulation platform.
- Carried out simulations to quantify the performance of the end to end the simulations underscored the tremendous potential of MIMO communications for achieving high throughput rates in highly dispersive harsh environments.
- Tested our initial protocols on a non-real-time 2x2 OFDM prototype system.
- Conducted field trails in typical indoor and outdoor environments using the non-real-time testbed.
    - Demonstrated achievable spectral efficiencies of up to 12 bps with a small 2x2 configuration
    - Demonstrated both indoor and outdoor applications of MIMO

- o Demonstrated and quantified improvement of the proposed 2x2 system over commercially available 802.11a systems.

The following is a list of achievements during the phase 1 options effort:

- A detailed (component level) design of the RF transeivers.
- Detailed calculations on the GOPS (giga operations per second) required for MIMO demodulation.
- Overhead optimization experiments resulting in a packet structure with minimal training and piloting overhead.

A possible phase 2 effort will build on this work and would deliver a complete MIMO SDR hardware platform operating in real time and delivering user data rates of as much as 0.2 Gbps in multipath rich environments. Milestones in a phase 2 study would include

- Complete schematic and layout of the RF transceiver boards.
- Portation of both the signal processing and communications algorithms to target FPGA/DSP platforms
- Manufacturing of the RF board
- Unit testing of the RF
- Unit testing of the transceiver baseband boards in loop back configuration
- Testing of the MIMO SDR in controlled laboratory environments (this requires the baseband and the RF to be fully operational and integrated with one another)
- Field testing of the MIMO SDR in typical urban settings in Los Angeles
- Field testing of the MIMO SDR in typical military field environments

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